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CONF-840655--1

TITLE: Manufacture and Characterization of Self-Centering Carbon Fiber/Epoxy Matrix Composite Springs

LA-UR--84-2044

DE84 014012

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SUBMITTED TO: For presentation at 16th National SAMPE Technical Conference, Albuquerque, NM October 9-11, 1984

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FORM NO. 836 R4

CARBON FIBER/EPOXY MATRIX COMPOSITE SPRINGS AS SELF-CENTERING SUPPORTS: MANUFACTURE AND EVALUATION

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Abstract

A variety of engineering and experimental applications require primary support structures which are self-centering. High mechanical strength, low-density, carbon fiber/epoxy matrix composite springs are used in unique planar, cylindrical, conical, and spherical configurations to self-center components. The sinusoidal and triangular-shaped composite springs are readily manufactured and assembled into component hardware. Design considerations, flexural strength properties, load bearing and centering data plus procedures for the manufacture of composite springs are presented.

Keywords:
self-centering spring
carbon fiber reinforcement
epoxy matrix binder
composite spring

1. INTRODUCTION

The purpose of this investigation was to devise a configuration and method for supporting components within planar, cylindrical, conical, and spherical configurations. It was desirable that the support structure have high mechanical strengths, low density, and provide the alignment necessary to achieve planar, axial, and spherical self-centering of components. Furthermore, it was also desirable that the support device be easily manufactured, require a minimum of machining or dressing prior to use, and lend itself to conventional means of attachment, typically by adhesive bonding or pinning.

Applications for self-centering structures are manifold. These include, but are not limited to mirrors and shielding in planar configurations; cooling and heating ducts; centering of reactor fuel rods and solar heating devices for cylindrical shapes; maintaining center of gravity in conical shaped re-entry vehicles; and explosive studies, and space shuttle and magnetic fusion experiments for spherical configurations.

2. MATERIALS AND PROCESSING

2.1 Composite spring design and manufacture

2.1.1 Material selection. Advanced composites based on carbon fiber and Kevlar (a polyphenylene terphthalamide crystalline fiber reinforcement) with epoxy resin binders provide high strength-to-weight ratio structures commonly used by the aircraft industry. Although Kevlar provides a tougher composite, it does not have the high modulus and strength in compression inherent in carbon fibers. For this reason, initial investigative efforts were directed to the development of a carbon fiber/epoxy matrix composite as a candidate material for composite springs.

2.1.2 Spring design considerations. Other than carbon fiber type and epoxy matrix, there are design considerations that affect the performance of the composite spring as shown in Fig. 1. These include the contact angle radii; the spring length, thickness, and width; the angles of the spring; and any filleting of adhesive at the spring/substrate contact angle.

2.1.3 Mold design. Three-part split molds are designed for planar and cylindrical shapes to produce a one piece, six point contact, self centering spring (Fig. 2). The o.d. i.d. dimensions are increased 0.25 mm in order to place the spring in compression and improve centering characteristics. By milling grooves 0.5 mm in depth along the width of the spring, parts can be produced that do not require machining. Any necessary deflashing can be done with a belt sander. Initially, the design provided contacts of equal length at the o.d.-i.d. nodal points. All radii were 0.635 cm. There were no design data for selecting this or any other radius. Other spring designs retained the original o.d. contact length but varied the i.d. to accommodate various internal designs; this necessitated a change in the i.d. contact length. Although a step series of six-point contact springs can be used, a single wide spring for a conical shape is more complex and requires a different mold design.

A spherical shape, although more complex, requires relatively simple two-contact point springs (Fig. 3) and four are needed to center a sphere within a sphere in a tetrahedral configuration.

2.1.4 Silicone pressure pad preparation. The function of the silicone pressure pad is to provide lateral pressure, thereby forcing the carbon fiber epoxy prepreg tape into the milled grooves of the mold during cure in the press. The mold is placed on a silastic pad in a autoclave. Dow Corning RTV 3120 silicone rubber or RTV 3110 is mixed with catalyst S, degassed, and then poured into the mold. The silicone is cured at 65°C under 5.6 kg cm^{-2} pressure for 16 hours. After curing the silicone pad is removed from the mold and trimmed. A Viton rubber insert is also used to force the RTV silicone against the prepreg tape during press cure.

2.1.5 Prepreg tape preparation. Commercially available prepreg tapes can be used to prepare the composite springs. However, the tape can be prepared in the laboratory when only a few hundred grams of material are needed for a given application. In these instances, Mylar film was taped to both sides of a 15 x 75 x 1.8 cm wood board with 0.635 mm spacings between sets of nails at the ends. Eleven strands of Union Carbide PAN based carbon fiber or 14 strands of Hercules AS-4 PAN based carbon fiber were hand wound between the spacings to provide a parallel, unidirectional nesting of carbon fiber tow.

A pure diglycidal ether of bisphenol A (Dow Chemical's DER 332) was cured with a stoichiometric quantity of methylene dianiline, (4,4'-diaminodiphenyl methane) MDA. The MDA was liquified by heating to 90°C, epoxy resin was added, the mixture was stirred until visibly uniform and then was cooled to 50°C for use.

The resin/curing-agent mixture was brushed on the carbon filaments, and care was taken to adequately wet, but not oversaturate, the fibers with an excess of resin. The impregnated tape was allowed to B-stage at room temperature for approximately 36 hours or until the right degree of handling tack was obtained. The tape was then stored at -25°C until used.

2.1.6 Prepreg tape forming, cure and part dressing. A 6.35 mm band of prepreg tape was finger-pressed into a groove of the mold which had been coated with Camie mold release agent. Occasionally, a hot air gun was used to facilitate forming of the tape at the radii points. The single joint was scarfed and overlapped one (1) cm. The silicone pressure pad was inserted into the mold cavity assembly and backed with a rubber pad. The assembly was then placed in a compression press, two tons of pressure were applied, and the assembly was allowed to heat-cure for 90 minutes at 135°C. The mold was removed and disassembled after cooling. The cured springs were removed, separated, and the flashing removed by sanding on a belt sander. The adhesive contact points were also sanded to provide a roughened surface for adhesive bonding.

2.2 Composite-spring assembly

2.2.1 Planar configurations. Planar configurations are the easiest to complete. The springs are inserted in groove in the substrates for alignment and ied by adhesive bonding ...

dhesive bonding or some means chanical fastening is needed event slippage of the compo- around the springs. In this nce, an epoxy/versamid general se adhesive is adequate, ugh two-component urethanes almost equally well but have r short working times.

Cylindrical configurations. ally, cylinders are a ication of a planar configura- assembly however is more icated. A series of springs nded or mechanically attached ie of the substrates (usually Inner cylinder) which then is ted into the larger diameter der. Adhesive is then ted under each of the outer ct nodes for stability and mency (Fig. 5). Alterna- y, the inner core assembly may otated into precut grooves in outer cylinder wall which in adhesive.

Conical configurations. al configurations are fications of cylinders and are, iding on the cone angle, what easier to assemble.

Spherical configurations. ough the springs are readily icated, their placement within shells requires the use of a uring device (Fig. 6) to place springs at a 109.5° tetrahedral e. One set of springs is ed to a sphere and hemishell, the other spring set is bonded

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Adhesive is applied to the springs of this hemishell half and to the hemishell equatorial surfaces. The hemishell halves are then assembled (Fig. 8) and allowed to cure.

2.3 Composite Spring Characterization. Specific characterization criteria were selected for evaluating lightweight, high strength, self centering composite springs used as load bearing supports. From Fig. 9 it would appear that flexure and compression most likely are the two types of loading that the composite spring would be expected to see in end use.

2.3.1 Flexural strength properties of composite springs. Beam bending or flexure most nearly represent the type of loading the composite spring are expected to encounter in end use. Accordingly, miniature flexural specimens were cut from the composite springs. These specimens were taken from the three outer diameter section lengths in contact with the outer wall. The slightly curved specimens were tested, as nearly as possible, in compliance with ASTM D790-71 by MST-6 Physical Metallurgy Section. The results obtained are tabulated in Table I.

2.3.1 Load bearing characteristics of composite springs. A test fixture was designed (Fig. 10) for evaluation of the composite springs in a simple planar configuration. The disc and ring inserted into the grooves and bonded in place. Failure modes were for the "Y," inverted "Y," and perpendicular to the plane of loading. These are representative of the support and translational loading that the composite spring could be subjected to in end use. Results obtained for several o.d:i.d spring diameter ratios are tabulated in Table II and Fig. 11. Testing was performed by MST-6 Physical Metallurgy section.

2.3.3 Self centering characteristics of composite springs. The self-centering characteristics of composite springs were determined using the simple planar configuration that was used for load bearing studies. The adhesive bonded assembly was cured in a horizontal position on a sheet of Teflon film. The o.d./i.d. distances were measured at the six nodal contact points between the inner and outer substrates. These data are tabulated in Table III.

2.3.4 Carbon fiber resin matrix ratios. Within certain limits, the ratio of fiber reinforcement to binder directly relates to the mechanical strength properties of the composite, and the "Law of Additives" is applicable. Since carbon fibers are not affected by concentrated sulfuric acid, the resin content of the composite spring can be determined by dissolving the cured epoxy binder with sulfuric acid at 60°C. The the acid once the epoxy is dissolved, rinsed several times, with water, dried, and weighed. The volume percentage compositions of the composite are determined from known fiber and cured resin densities.

3. RESULTS AND DISCUSSION

The flexural strength properties tabulated in Table I were determined from "as molded" carbon fiber/epoxy matrix composite springs display the expected range of values consistent with fiber matrix-reinforcement ratios. Composite spring configuration is not a factor in this instance. A carbon-pitch fiber, Thornel VSB-32T, although having a high modulus, did not perform as well due to brittle fracture at lower ultimate strengths. Work was discontinued in favor of the "tougher" PAN based carbon fibers which served as the basis of this experimental work.

Assuming that a plane containing one self-centering spring is an element of a cylinder, load bearing tests should be applicable to both planar and cylindrical configutions. The spring is a three-point, (six nodal contacts) support system, therefore, bearing loads are associated with the "Y" and inverted "Y" orientations. Loads perpendicular to the plane of the spring are translational and not affected by the "Y" orientations. Support-load data from Table II and spring orientation and o.d.:i.d. ratio affect in-plane strength as well as out-of-plane translational loading. The smaller o.d.:i.d. ratios provide higher support loads, and the inverted "Y" position which is counterpart stronger than its. Since the spring angles were held constant on cylindrical configurations, part of this difference may be attributable to unequal cord lengths of the diameters at various o.d.:i.d. ratios. Thus at a high o.d.:i.d. ratio in the "Y" position, an applied load can function as a wedge, resulting in preliminary shear and adhesion failure. Test values perpendicular to the plane of the spring are significantly lower, noticeably at the higher o.d.:i.d. ratios. A force applied on this plane is not a bearing load but rather one of peel, shear, and adhesion when the smaller i.d. substrate is moved in and out of the spring plane. Although in-and-out of plane bending can be reduced by increasing the width of the spring at least at the contact points, it is not a cure-all, because excellent bonds between the spring and substrates are a prerequisite. The first signs of failure are in adhesion. This illustrated in Table II, and although it is not destructive to the integrity of the spring assembly it begins to occur by as much as 50 percent of the ultimate Table III, self centering is obtained as long as there is a small degree of compression in the spring assembly. Stabilization is required for permanency. Stabilization is achieved by adhesive bonding or pinning at the nodal contact points to obtain a truss-like structure. As illustrated in Table III, there appears to be no consistency in the self-centering of carbon fiber/epoxy matrix composite springs at various o.d.:i.d. ratios. Off-center deviations range from 0.004 to 0.008 mm. Normally it would be expected that the higher o.d.:i.d ratio springs, which provided less support, would be more likely to demonstrate maximum off-center deviations.

4. SUMMARY AND CONCLUSIONS

Two- and three-part breakaway compression molds were designed for the fabrication of carbon fiber/epoxy matrix composite springs. Molds have grooves for containment of the prepreg tape which is manually formed into place. A silicone pressure pad provides lateral pressure during cure at 135°C for 1.5 hours under low pressure. Springs are adaptable to planar, cylindrical, conical, and spherical configurations and can be used for a variety of applications requiring self centering. Flexure strength properties determined from the "as-molded" springs provided values of 1425–1940 MPa ultimate strength and moduli of 110-190 GPa at 48-54% fiber content by weight.

Although the composite springs automatically lend themselves to self-centering, stabilization is required for permanency. This is done by bonding the springs to the substrates with either a general purpose epoxy or urethane adhesive, or by mechanical attachment. This provides a stable truss which is capable of supporting many times the weight of the internal substrate both in the "Y" and inverted "Y" positions. Support load capabilities of composite springs are configuration dependent. Lower o.d:i.d. ratios support higher loadings than do higher ratios, and the inverted "Y" position provides the greatest load bearing capability. In most instances, failure of the composite springs [illegible] loading is preceded by a failure in adhesion at one or more of the nodal contact paints. At low o.d.:i.d. ratios, initial failure can also be by intralaminar shear within the composite spring. Ultimate failure (rupture) is generally in flexure in the inverted "Y" position. Transverse loads perpendicular to the plane of the spring fail at lower values than those measured at either of the "Y" positions. Failure is generally by adhesion and peel modes. Again, the higher o.d.:i.d. ratios have the lowest values. Improved adhesive-bonding techniques or alternate methods of fastening the composite springs in place are areas requiring further study and improvement.

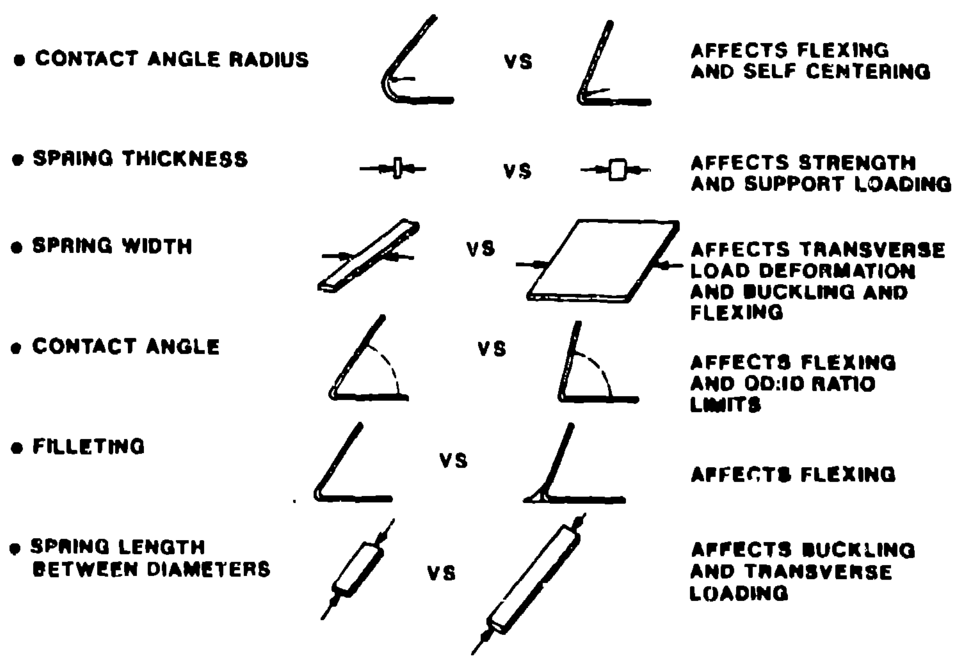

Fig. 1. Design considerations affecting performance of self-centering carbon fiber/epoxy matrix composite springs.

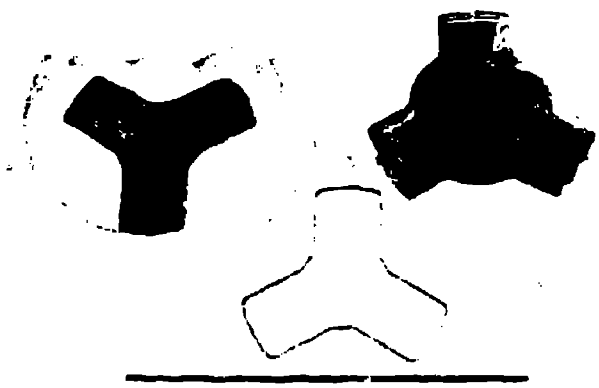

Fig. 2. A three-part split mold with retainer ring, silicone pad, composite spring and prepreg tape.

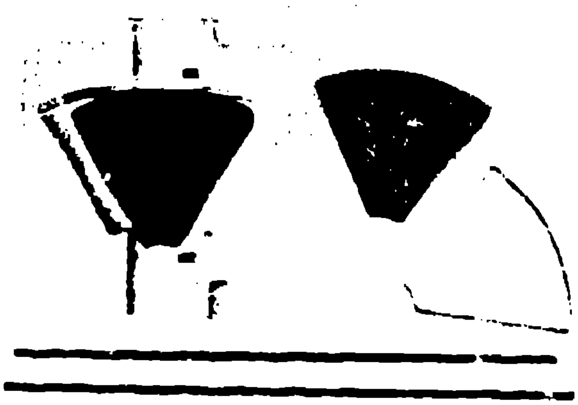

Fig. 3. A two-part split mold with silicone pad, composite spring and prepreg tape.

Fig. 4. Self-centering composite spring in a planar configuration.

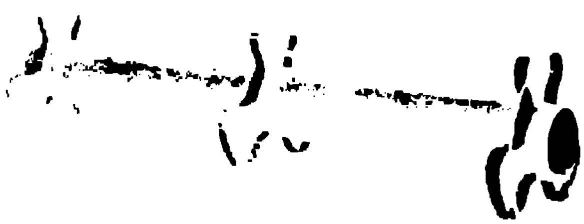

Fig. 5. Self-centering composite springs on a cylindrical configuration.

Fig. 6. Fixturing device for preparing a self-centering spherical configuration.

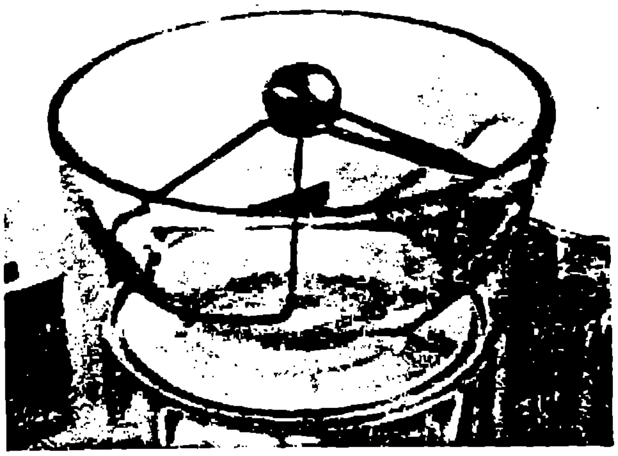

Fig. 7. Sphere supported by composite springs within a hemishell.

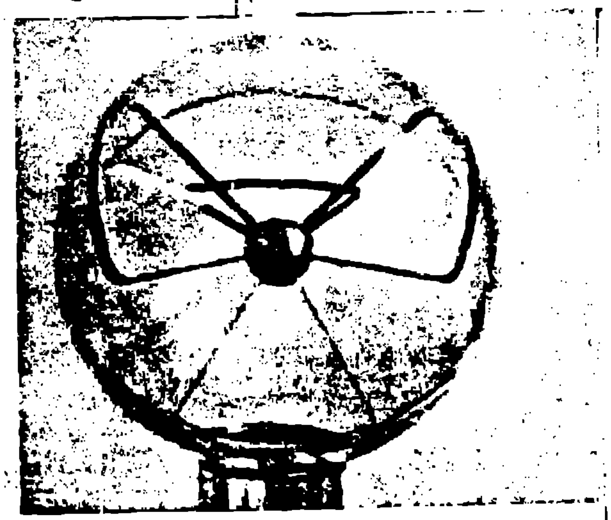

Fig. 8. Self-centering springs in a spherical configuration.

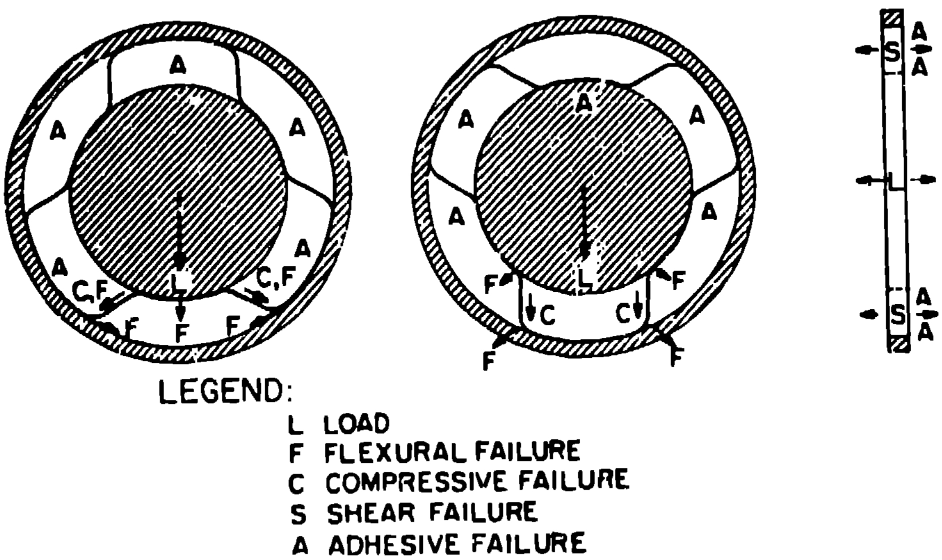

Fig. 9. Failure modes for carbon fiber/epoxy matrix composite springs.

Fig. 10. Test fixture for determining support load strengths of carbon fiber/epoxy matrix composite springs.

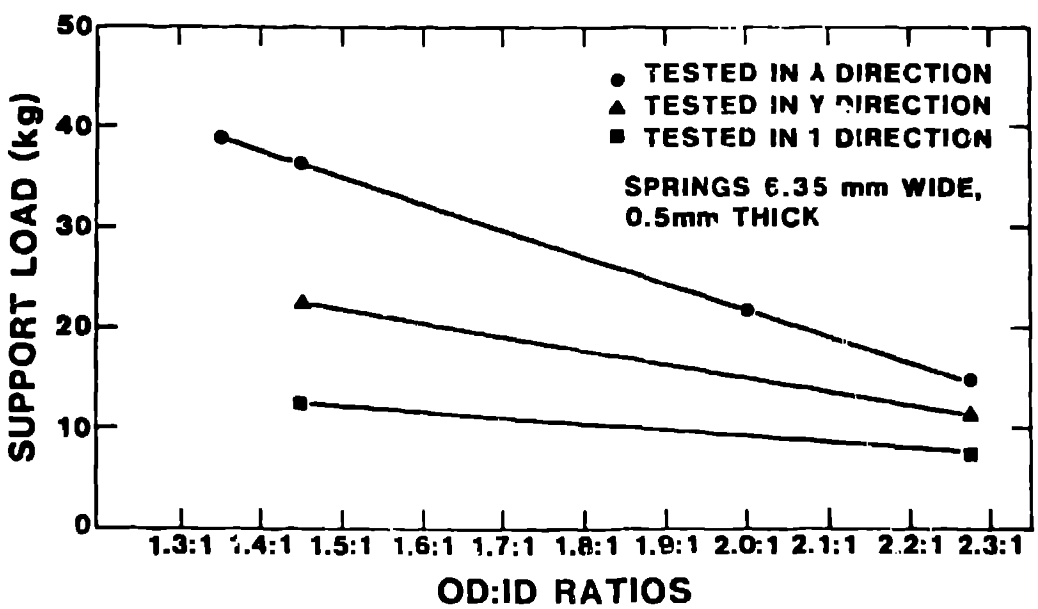

Fig. 11. Support load strengths of composite springs in three orientations and at several OD:ID ratios.

TABLE I

FLEXURAL STRENGTH PROPERTIES OF UNDIRECTIONAL CARBON FIBER/EPOXY MATRIX COMPOSITE SPRINGS

FLEXURAL STRENGTH		FIBER CONTENT	
ULTIMATE (MPa)	MODULUS (GPa)	WEIGHT (%)	VOLUME (%)
1941	191	53.46	43.78
1772	165	52.36	42.70
1682	161	49.89	40.30
1427	112	47.85	38.32

MATRIX: DOW CHEMICAL, PLASTICS DEPARTMENT; DER 332/METHYLENE DIANILINE (4, 4' – DIAMINODIPHENYL METHANE), DENSITY 1.20

FIBER: UNION CARBIDE CORPORATION, CARBON PRODUCTS DIVISION; THORNEL 300, 33 M psi MODULUS, DENSITY 1.77

TABLE II

SUPPORT LOAD CHARACTERISTICS OF CARBON FIBER/EPOXY MATRIX COMPOSITE SPRINGS

SPRING		ULTIMATE SUPPORT LOAD (kg)			FAILURE MODES	
OD:ID RATIO	WEIGHT (g)	A DIRECTION	Y DIRECTION	I DIRECTION	ULTIMATE	INITIAL (g)
1.352:1	2.6 - 2.7	38.77	–	–	FL	AD 20.45
1.450:1	3.4 - 3.5	36.36	–	–	CO	AD 19.55
1.450:1	3.4 - 3.5	–	22.05	–	FL	AD 4.18
1.450:1	3.4 - 3.5	–	–	12.28	AD	AD 5.37
2.005:1	2.9 - 3.1	21.82	–	–	FL	AD 17.27
2.270:1	3.4 - 3.7	15.00	–	–	AD	AD 5.80
2.270:1	3.4 - 3.7	–	11.36	–	FL	AD 5.45
2.270:1	3.4 - 3.7	–	–	7.15	AD	AD 4.92

CODE: FL – FLEXURE FAILURE
CO – COMPRESSION FAILURE
AD – ADHESION FAILURE

ALL SPRINGS 6.30 – 6.35 mm WIDE, 0.56 – 1.60 mm THICK

TABLE III

CENTERING CHARACTERISTICS OF CARBON FIBER/EPOXY MATRIX COMPOSITE SPRINGS

SPRING	OD - ID DIFFERENCES AT 180° NODAL MIDPOINTS (cm)						MAXIMUM DEVIATION (cm)	
OD:ID RATIO	A	D	B	E	C	F	180°	OFF-CENTER
1.352:1	2.220	2.222	2.226	2.220	2.231	2.219	0.012	0.006
1.450:1	3.111	3.106	3.118	3.108	3.117	3.109	0.010	0.005
2.005:1	4.566	4.558	4.557	4.565	4.568	4.560	0.008	0.004
2.270:1	5.542	5.550	5.551	5.540	5.554	5.538	0.016	0.008